

High energy collisions of strongly deformed nuclei: An old idea with a new twist

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UU collisions can provide about 30% larger densities compared to central PbPb ones. New aspect is generation of rather deformed initial states. We show that those can be effectively used to resolve a number of outstanding issues, from corrections to hard processes, elliptic flow (the QGP push issue), and the mechanism of J/ψ suppression. UU collisions are studied by a simple Monte-Carlo model, and it is shown how selecting two control parameters - the number of participant nuclei and deformation - one can select particular geometry of the collision.

I. INTRODUCTION

An “old idea” mentioned in the title is to select the head-on “long-long” collisions, by simply triggering on maximal number of participants N_p . Although it is kind of a folklore of the field, the only written material on it I found is a memo [1] written by P.Braun-Munzinger. His estimates show that, due to larger A and *deformation*, the gain in energy density for UU over AuAu* can reach the factor 1.8. Although our study had found smaller numbers, new applications are proposed. They are mostly related with a different geometry of the collisions, the parallel one, which incorporates about the same energy density as available in central PbPb collisions, with significant deformation.

The general attitude of this study was to look how UU collisions can help to understand the existing open issues of the SPS heavy ion program. It certainly is of interest to RHIC program, although it is probably premature to discuss it now. The emphasis is made here on event selection, and other interesting options (like using targets with crystals with naturally aligned U) are not studied.

Let me start with outlining simple argument for head-on collisions. Representing U as a homogeneous ellipsoid with one long (R_l) and two short (R_s) semi-axis, one can related their ratio to deformation parameter δ used in nuclear physics (see e.g. [2])

$$\frac{R_l}{R_s} = \left(\frac{1 + 4\delta/3}{1 - 2\delta/3} \right)^{1/2} \quad (1)$$

For $\delta_U \approx .27$ this ratio is 1.29, the basic deformation ratio to be used below.

It is convenient to think first in terms of “wounded” or “participant” nucleons first, a purely geometric concept, and only then consider real multiplicity (entropy) production. (We will follow such logic throughout the paper.) Let us thus start with comparing the density of participants per transverse area $n_p = N_p/(\pi R_s^2)$, for “long-long” collisions of the deformed nuclei vs the spherical one with *the same* A and $R = (R_s^2 R_l)^{1/3}$. The effect only comes from reduction of the area, so

$$\frac{n_p^{deformed}}{n_p^{spherical}} = \frac{A^{deformed}}{A^{spherical}} \left(\frac{R}{R_s} \right)^2 \quad (2)$$

For A=238 we will use $R_l = 8.4$, $R_s = 6.5$, $R = 7.0 fm$, and so deformation alone increase the n_p by 1.16. For U and Pb ($R_{Pb}=6.78$ fm in such model) one gets the participant density gain 1.24.

Transferring this into initial entropy density, one should recall that for (spherical) AA collisions

$$\frac{dN}{dy}(y=0) \sim A^{1+\alpha} \quad (3)$$

with $\alpha \approx .12$. So, assuming as usual that final multiplicity is proportional to the initial entropy density, we see that there is a correction to the simple idea that each participant nuclei gives the same (energy dependent) contribution to the spectrum. This non-zero α incorporates both (i) additional increase in multiplicity, and (ii) extra stopping (shift toward mid-rapidity): we are only interested in their combination $dN/dy(y=0)$. Furthermore, it is natural to think that transverse dimensions of the system enter trivially here, and so these extra effects due to increased density. With this additional factor $\sim n_p^{3\alpha}$ we obtain the UU/PbPb *total initial density gain*[†] $1.24^{1+3\alpha} = 1.34$.

The main questions addressed in this paper are two-fold. One is to make some realistic estimates of the effect, not just for a particular configuration but for ensemble of events selected by some *experimentally accessible* criteria. The second is to outline possible applications of high energy collisions of the deformed nuclei.

II. UU COLLISIONS VERSUS PBPB: THE SIMULATION

Simple Monte-Carlo program was written, which initializes nucleons inside nuclei and follow their paths

[†]At fixed time after the crossing, a la Bjorken. If more stopping means earlier equilibration, the available density is larger.

*Below we use PbPb instead.

through another one. Since we are not really interested in peripheral collisions, we did not include diffuse boundary of nuclei and used the ellipsoids described above. We also ignored probabilistic nature of the interaction, considering transverse distance between nucleons $R < (\sigma_{in}/\pi)^{1/2}$ to be sufficient reason to make both of them participants. So, the only source of fluctuations[‡] are random positions of the nucleons inside the nucleus.

Spherical nuclei have only one parameter - impact parameter b - which in such classical treatment determines the mean number of participants. Deformed nuclei have in general 5 such parameters: b and 4 spherical angles $\theta_i, \phi_i, i = 1, 2$ indicating the orientation of their longer axes at the collision moment. The main objective of the calculation is to see how well one can actually fix those, by using experimentally available information.

Few words about our definitions. After all participant nuclei are identified, we calculated the tensor

$$T_{ij} = \langle x_i x_j \rangle \quad (4)$$

in transverse plane, diagonalize it and find its eigenvalues R_+, R_- . The density of participants we use below is defined as $n_p = N_{part}/(\pi R_+ R_-)$ and deformation as R_+/R_- .

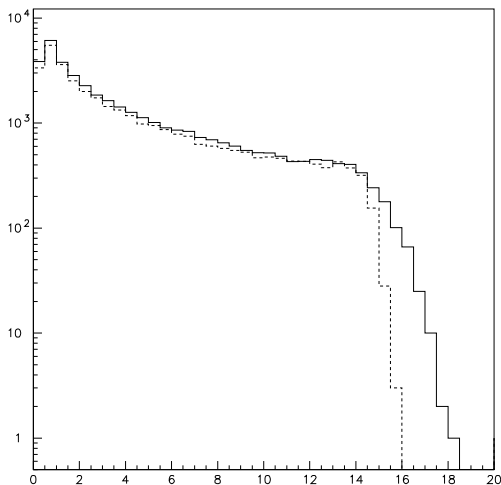


FIG. 1. Density distribution with selection $N_p > 0.9(2A)$. Solid (dashed) are for UU and PbPb collisions

If no selection is made, the density of the participants n_p shown in 1 is very similar, except for the tail region. A gain in n_p of the order of 16% seem indeed possible, with reasonable loss of statistics. However, if one introduces “centrality” cuts, the situation is different. We would define a fair “centrality cut” by restricting $N_p > 0.9(2A)$,

with corresponding A for both cases. Triggering on large N_p (or forward energy) one effectively eliminates spectators (and many complicated geometries).

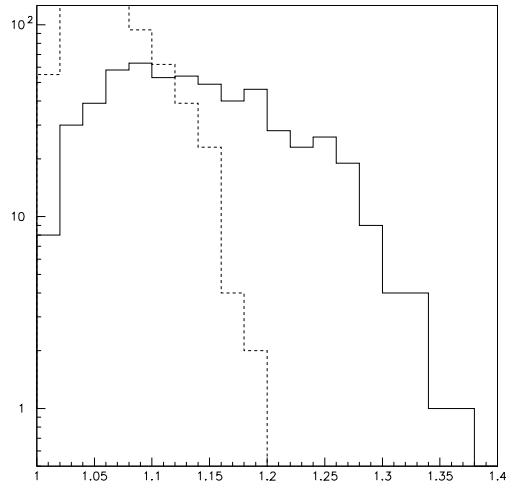


FIG. 2. Distribution of R_+/R_- (long-to-short semi-axis in transverse plane), with selection $N_p > 0.9(2A)$. Solid (dashed) are for UU and PbPb collisions

The first striking feature one finds after such cut is that distribution of the deformations of the initial 2d ellipsoid R_+/R_- is very different: see figure Fig.2. The ratios as large as 1.35 are accessible, while in PbPb collisions all the “central” collisions are very spherical. The maximal deformation, not surprisingly, is of the order of deformation of U[§] Those correspond to collisions with two long directions parallel to each other and orthogonal to the beam. It is about the same as is obtained for medium b for spherical nuclei, but at larger energy density and larger system (see below).

The joint distributions in participant density - deformation plane for (most central) UU and PbPb collisions are compared in Fig.3(a,b). The main message one can get from it is that strong correlation between the deformation and density, existing for spherical nuclei, is to some extent relaxed for UU.

How one can measure the 2d deformation of the initial conditions? The measured elliptic deformation of spectra of secondary particles, pions or nucleons, v_2 , is proportional to this initial deformation (with EOS depending coefficient) and should have similar distribution. divide measured distribution over v_2 into more and less deformed.

Suppose now that one uses both control parameters,

[‡]And it is by no means assumed to be accurate account for fluctuations.

[§]Note that it is comparable to what is obtained for medium b for spherical nuclei, but now reached for larger energy density and larger system.

N_{part} and v_2 . Is it really possible to select the *particular geometries* of the collisions we want? In Fig.4(a) one can see that it is to a significant effect correct: the *less – deformed* sample is rich in the region $\cos\theta \approx 1$, or in “head-on” collisions, while the *more – deformed* collisions have none of them, and concentrate at small $\cos\theta$. In Fig.4(b) one can see that the same selection of events correspond to the *difference* of the azimuthal angles $\phi_1 - \phi_2$ to be peaked around 0, or have a flat distribution, respectively.

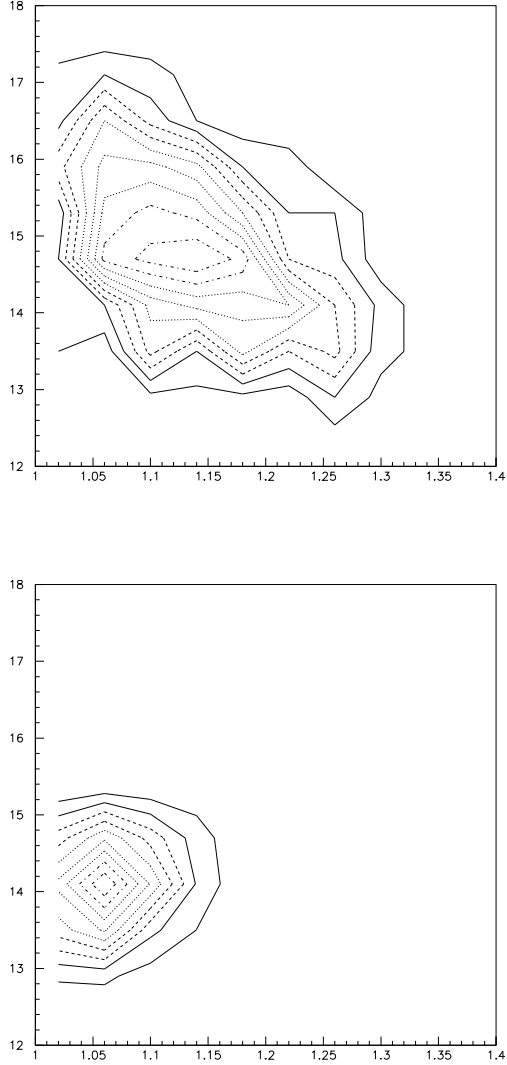


FIG. 3. Distribution over participant density n_p [fm^{-2}] vs deformation R_+/R_- , for (a) UU ($N_{part} > 428$) and (b) PbPb ($N_{part} > 374$) collisions, respectively.

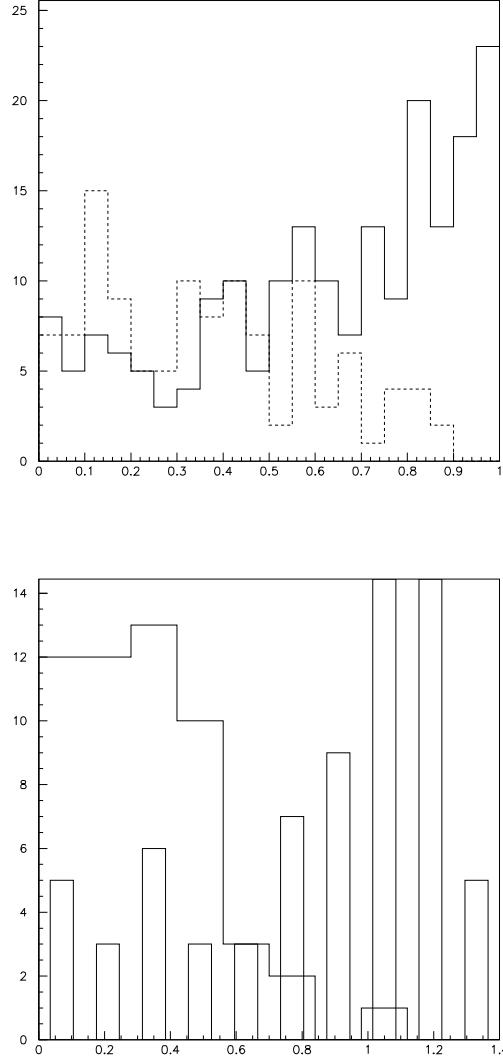


FIG. 4. Distributions of original angles for UU collisions, $N_p > 0.9(2A)$. (a) Distribution in $\cos(\theta)$, the angle between the long axis of U and the beam. The solid (dotted) histograms are for less deformed ($R_+/R_- < 1.1$) (more deformed $R_+/R_- > 1.2$) initial states. (b) Distribution in difference between polar angles $|\phi_1 - \phi_2|$, solid (barred) histograms are for less and more deformed collisions, same selection.

Finally note also that the figures presented above have shown only the density of participants n_p : let us now recall the correction factor $\sim n_p^{3\alpha}$ we discussed in the Introduction for the initial energy density. It can be seen as additional non-linear deformation of the axis, when going from n_p to dN/dy . The contrast between UU and PbPb in dN/dy is larger by another 8%. Note also, that we have only discussed local quantities, like participant density n_p . For many applications the absolute size of the system is of similar and sometimes even larger importance.

III. POSSIBLE APPLICATIONS

A. Hard versus soft processes

The so called *hard* processes include Drell-Yan dilepton production, two-jet events, heavy flavor production etc. Those are described in the first order by the parton model, and so are the simplest to treat for any geometry. For example, for head-on collisions discussed in the introduction, the output should be simply

$$\sigma_{hard} \sim R_z^2 R_t^2 \quad (5)$$

Significant interest is related with various QCD *corrections* to the parton model: some of them are related to *initial state* re-scattering, and some to the *final state* ones. Examples of the former are “shadowing” of nuclear structure functions and increase in parton p_t , the latter processes lead to the so called “jet quenching” or energy losses. The debates about their relative contributions continues: one, at one talk as a semi-joke I proposed to consider rectangular nuclei with different R_z, R_t to separate them. Now we propose a particular realization of this idea.

How large level arm do we have, with UU collisions? For head-on collisions (discussed above) $R_z = R_l, R_t = R_s$, while for “parallel collisions” with maximal deformation it is the other way around, $R_z = R_s$ and *one* of the $R_t = R_l$. So the ratio R_z/R_t varies between about 1.3 and 1/1.3, or a span of 1.7. This may be enough to disentangle different mechanisms.

B. Ellipticity and EOS

In high energy collisions the shape of the “initial almond” for non-central collisions leads to enhanced “in-plane” flow, in direction of the impact parameter [4]. It is very important because (as pointed out in [5](a)) it is developed *earlier* than the radial one, and thus it may shed light on Equation of State (EOS) at early time. The particular issue is whether we do or do not have QGP at such time, at SPS or RHIC. Recent review of ellipticity one can find in [7].

Ellipticity is now measured by the asymmetry of the particle *number*, or v_i harmonics defined as

$$\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{v_2}{\pi} \cos(2\phi) + \frac{v_4}{\pi} \cos(4\phi) + \dots \quad (6)$$

rather than asymmetry of the momentum distribution, which was used more at low energies. Furthermore, v_i are often additionally normalized to the spatial asymmetry of the initial state (the “almond”) at the same b , $\alpha_2 = (R_+^2 - R_-^2)/(R_+^2 + R_-^2)$ in order to cancel out this kinematic factor and to see the response to asymmetry.

There are two ways to look at elliptic flow: by using collision energy dependence, or centrality dependence at

fixed beam. The first method is more difficult, but it deals with fixed geometry and only slowly changing size of the system and relevant densities. For recent discussion of it see ref.3. The *centrality* dependence is easier to measure, but interpretation is more complicated, because increasing b we make “almond” more elliptic, but also much smaller and thinner: eventually finite size corrections reduce pressure build-up. This is of crucial importance for the “QGP push” issue at SPS, since it should be present only for the largest densities available, and at small b the v_2 is very small and difficult to measure.

Preliminary NA49 data presented at QM99 [6] may indeed indicate “the plasma push”, as enhancement of v_2 at small b . However much more work is clearly needed to understand this complex interplay of EOS and finite size effects.

U collisions discussed below in principle provide the means to decouple finite size and deformation issues. In particular, the deformation of U (about 1.3) is actually enough to generate well measurable v_2 of the order of several percent, without significant loss in density.

C. J/ψ suppression

One of the most intriguing observables, the J/ψ suppression, is unique in its significant centrality and A-dependence. Here is not a place to discuss it in any details, but let me make few remarks about recent developments.

New NA50 data reported at QM99 have clarified the situation for the most central collisions: using now very thin target, it was found that 1996 data suffered from multiple interactions. In fact there is a significantly stronger suppression at small b . Furthermore, it seem like the two component picture, with separate χ and ψ thresholds, really emerges. In view of this, it is desirable to increasing the density and/or the famous variable L : only deformed U provides an opportunity here at SPS.

In order to discriminate experimentally different ideas on the nature of J/ψ suppression, we should be able to tell whether suppression happened quickly or need a longer time. The old idea is to study suppression dependence on p_t . Unfortunately changing p_t we also change the kinematics: e.g. destruction by gluons or hadrons go better if p_t grows.

Maybe better idea [8] is to use azimuthal dependence of the suppression. Instantaneous suppression should show *no* asymmetry, but if it takes few fm/c the anisotropy should show up. However, as for the elliptic flow, the problem is the initial “almond” at $b < 8$ fm is not very anisotropic, and for larger b there is no anomalous suppression.

Here too the deformed U can help, providing (with trigger conditions discussed above) a variety of geometries, including the “parallel collisions”.

IV. ACKNOWLEDGEMENTS

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